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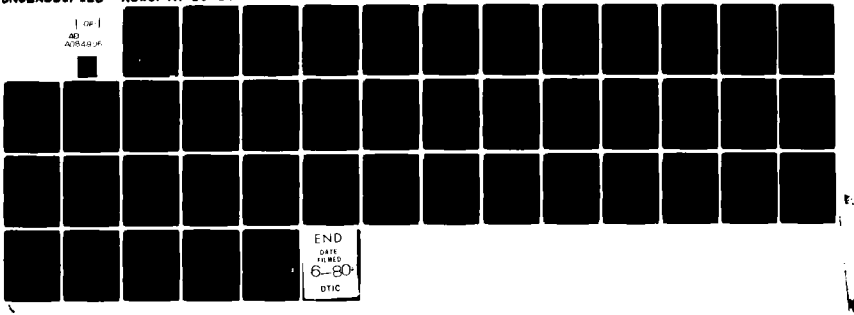

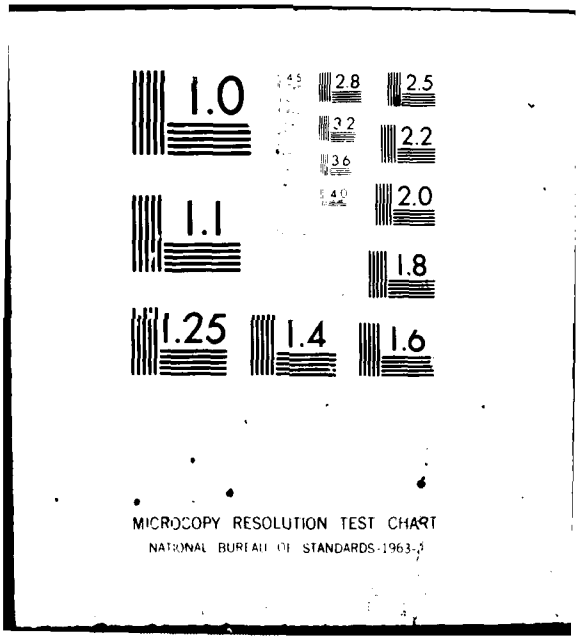
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DDT BEHAVIOR OF POROUS PROPELLANT MODELS AND POROUS SAMPLES OF COMMERCIAL PROPELLANTS

BY DONNA PRICE RICHARD R. BERNECKER

RESEARCH AND TECHNOLOGY DEPARTMENT

13 MARCH 1980

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A number of binary mixtures, components of which are propellant ingredients, were examined in steel walled tubes for their DDT behavior at 60-70% theoretical maximum density (TMD). Several commercial propellants and one 4-component, composite model were also examined. A number of compositional effects were noted and reported. Some propellants, at high porosity, showed reaction not detectable by our ionization probes. For propellants which exhibited transition at 70% TMD in our apparatus, the range in predetonation

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column length (ℓ) was 103-170 mm and in relative time to detonation, 76-247 μs.

FOREWORD

This report was prepared under Task ZR0130901, IR-159. The work was an exploratory investigation to obtain an overview of propellant sensitivity to deflagration to detonation transition (DDT). The present results and conclusions on the DDT behavior of highly porous propellant models and propellants should be of interest in the areas of explosive sensitivity and of propellant safety.

Ira M Blatstein for
JULIUS W. ENIG
By direction

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INTRODUCTION

The present work was undertaken as an exploratory investigation of propellant (i.e., composite explosive) sensitivity to undergoing a transition from burning to detonation. The tendency of a propellant to exhibit a deflagration to detonation transition (DDT) is becoming increasingly important as propellant grains are made larger and the amount of their explosive component (e.g. HMX, NC, NG) is increased. It was the purpose of this preliminary work to obtain a broad overview, with large variations in composition, of this sensitivity area in order to select a good experimental approach for its study.

It is generally recognized that the explosive behavior of propellants is greatly enhanced by the presence of porosity. Hence the experimental work was carried out at about 60-70% theoretical maximum density (TMD). A systematic variation of the porosity or of the compositions was not attempted at this time.

The charges used consisted of a single propellant component which is also a high explosive, nitrocellulose (NC), various mechanical binary mixtures consisting of pairs to be found in commercial propellants and composite explosives, and a single 4-component model. The commercial propellants examined were a gun propellant (M-7, essentially a double base NC/NG composition), a gas generator (Arcadene, plastic bonded HMX), and two rocket propellants (FKM and VLU). FKM is a composite propellant with HMX added; VLU is a composite modified double base (CMDB) propellant and is also referred to as a cross-linked double base (XLDB) propellant.

EXPERIMENTAL

INSTRUMENTATION AND PROCEDURES

The experimental setup and procedures have been described in detail elsewhere[1,2]. The apparatus consists of a seamless steel tube with heavy end closures. The column length of the 0.35 g of 25/75 B/KNO_3 ignitor is 6.3 mm; the length of the explosive column is 295.4 mm. Each pressed charge is examined by X-ray prior to its instrumentation.

[1]Bernecker, R. R. and Price, D., "Studies in the Transition from Deflagration to Detonation in Granular Explosives," Combust. Flame, Vol. 22, 1974, 111-117, 119-129, and 161-170. See also NOLTR 72-202.

[2]Price, D. and Bernecker, R. R., "Sensitivity of Porous Explosives to Transition from Deflagration to Detonation," Combust. Flame, Vol. 25, 1975, 91-100. See also NOLTR 74-186.

The DDT tube is instrumented with ionization probes (IP) and strain gages (SG) to monitor ionization fronts and internal pressure, respectively. For brevity, henceforth ionization probes will be referred to as probes; strain gages, as gages. As before[1], both custom-made and commercial probes are used; distance-time (x-t) data from each are distinguished on the graphs. The number of gage locations for monitoring internal pressure is generally four or five per tube. The gage output is reported in strain (ε) or microstrain ($\mu\varepsilon$). In a static calibration of the tube, the gradient is 112 $\mu\varepsilon$/kbar up to the elastic limit at 2.2 kbar. From 2 to 4.7 kbar, the microstrain increases from 225 to 788.

One difference in procedure from that reported in Reference 1 is in the determination of the predetonation column length, ℓ. In the case of 91/9 RDX/wax, it was possible to use the intersection of the postconvective wave front with the extrapolated detonation front to locate ℓ in the x-t plane; the value was confirmed by that obtained from tube fragments. Here and, in general for HE other than 91/9 RDX/wax, ℓ is more reliably determined from markings on the tube fragments; it is checked for consistency with the probe and gage records in the x-t plane. In the present work, there were a few shots for which tube fragments did not give an unambiguous value of ℓ. These are discussed in the Appendix and listed in Table A1. Unless otherwise indicated, ℓ values were measured to ± 3 mm.

Values for x were measured from the ignitor/explosive interface. Relative time values were measured from the first discharge of the triggering IP; this was generally the first probe.

MATERIALS

The ammonium perchlorate (AP) used was propellant grade and contained 0.2% tricalcium phosphate. It was ground at the Naval Ordnance Station (Indian Head, MD). The lot used for this work had a weight mean particle size of 8 μm by micromerograph. The aluminum used was dichromated spherical powder supplied by Valley Metallurgical Processing Company. It was designated H-5 and had an average particle size of 7 μm by Fisher subsieve sizer. The wax used was a refined, powdered, grade 1 yellow carnauba wax supplied by Frank B. Ross Company; its average particle size was about 125 μm. The explosives were obtained commercially and satisfied the relevant military specifications. RDX was Class A ($\delta \sim 200\mu$); HMX, Class E ($\delta \sim 15\mu$). The nitrocellulose (NC) was obtained through NOS, Indian Head, MD. It was an Olin Matheson fluid ball powder, Type A; it is essentially NC ($\delta \sim 40\mu$) which is nominally 12.6% nitrogen and contains about 1% 2-nitrodiphenylamine stabilizer and 0.2-0.3% coating material. The gun propellant, a modified M-7, was also obtained from NOS/IH, and shredded in our Laboratory (See Appendix). The other three propellants, in shredded or powdered form, were obtained from their respective manufacturers. All dry mixing was carried out by the procedure of Reference 3.

[3]Price, D., Clairmont, A. R., Jr., and Erkman, J. O., "Explosive Behavior of Aluminized Ammonium Perchlorate," Combust. Flame, Vol. 20, 1973, 389-400.

EXPERIMENTAL RESULTS AND DISCUSSION

A total of fifteen shots were made. Detailed tables, records for each shot, and discussions of them appear in the Appendix. Table 1 contains a summary of the results. As that tabulation shows, the charges have been divided into four groups; that classification is roughly in accord with their composition.

The first group consisted of binary AP mixtures that might be expected in composite or CMDB propellants. Each of the three charges was 80% AP. AP/wax was fired at 56.6 and 67.0% TMD; AP/Aℓ, at 56.8% TMD. As Table 1 shows, all three failed to transit to detonation, but all three burned readily. In fact, the velocities of the reactive fronts detected by IPs are much higher than would be expected for a convective front at these high porosities. Russian workers[4] report that the breakdown of conductive burning and the appearance of convective burning occurs for AP/bitumen mixtures at a much lower critical pressure than it does for organic HE. This is probably also the case for AP/wax, and, if so, the burning is already greatly accelerated by the time of response of the IP 41 mm from the igniter. The same effect was seen in AP/Aℓ where the first IP was at x = 80 mm. In every case, the velocity of the IP front was no longer accelerating; it was either constant or falling slightly. Other Russian workers[5] have reported that a stoichiometric mixture of AP/polystyrene did exhibit DDT at 40 and 55% TMD, but not at 75% TMD. Thus it is possible that the three AP mixes at larger porosities or different compositions or both would show a transition. All three are detonable under shock initiation.

The second charge group consisted of binary mixes of RDX/Aℓ which might appear in either a CMDB or a composite propellant to which RDX has been added. The Aℓ content was 9 or 20% and each composition was tested at 70 and 90% TMD; all exhibited DDT. Again, as in the previous group, by the time the reaction had reached the first IP, it was well advanced in the two charges with 9% Aℓ. RDX (10-20μ) has a critical breakdown pressure about twice that of the AP mixture[4] but the RDX used here with $\bar{\delta} \sim 200\mu$ will have a lower breakdown pressure. Moreover, its acceleration after the onset of the convective flame front may be greater. When the Aℓ content was increased to 20%, the transition was sufficiently slowed to exhibit an IP front velocity of the magnitude of that expected for a convective flame front at the given porosity. Increasing the porosity also slowed down the DDT process. Hence the 80/20 RDX/Aℓ at 70% TMD produced records that can be completely resolved. These records (Fig. A7) show a process completely in accord with the physical model of DDT describing the transitional behavior of 91/9 RDX/wax at all compactions[1]. In other words, following a convective flame front traveling at about 0.3 mm/μs, a

[4] Belyaev, A. F., Korotkov, A. I., and Sulimov, A. A., "Breakdown of Surface Burning of Gas-Permeable Porous Systems," Combust., Explosion, and Shock Waves, Vol. 2, No. 3, 1966, 47-58.

[5] Korotkov, A. I., Sulimov, A. A., Obmenin, A. V., Dubovitskii, V. F., and Kurkin, A. I., "Transition from Combustion to Detonation in Porous Explosives," Combust., Explosion, and Shock Waves, Vol. 5, No. 3, 1969, 315-325.

TABLE 1 SUMMARY OF RESULTS

Shot No.	Material	ρ_o g/cm^3	% TMD	Predetonation Velocities: B IP front mm/μs	Predetonation Velocities: V Compression wave mm/μs	Predet. Col. Length ℓ mm	Relative times: $41_{\Delta t_D}$ μs	Relative times: $41_{\Delta t_D}$ μs	Detonation Velocity: D mm/μs	Detonation Velocity: σ mm/μs	
805	80/20 AP/Wax	1.10	67.0	0.64 - 0.58	1.0	F	-	-	-	-	Compression front precedes IP Front which is slightly convex upward
809	"	0.93	56.6	0.73	0.6	F	-	-	-	-	" "
906	80/20 AP/Aℓ	1.17	56.8	0.8 - 0.7	0.5	F	-	-	-	-	" "
1012	91/9 RDX/Aℓ	1.667	89.6	2.6	-	59	7.0	-	7.56	0.34	
1109	"	1.324	71.2	1.7	-	58	9.0	-	6.48	0.03	
1118	80/20 RDX/Aℓ	1.734	89.8	1.0	-	92 ± 10	25.0	-	∿7.8	-	
1203	"	1.359	70.4	0.3	0.8	87	173	49	5.56	0.07	
810	NC	0.947	59.9	0.37 - 0.42	0.8	163	257	141	4.81	0.24	
905	80/20 NC/Aℓ	0.980	57.0	0.3 - 0.7	0.7	F	-	-			Triggered on third probe
1101	NC	1.097	69.4	0.55 - 1.3	1.2	165	145	105	5.49	0.16	
1008	85/15 NC/AP	1.135	69.8	1.8	-	63	11.3	-	5.70	0.06	
1005	91/9 HMX(E)/AP	1.324	69.5	0.98	-	86	35.5	-	6.53	0.16	Class E HMX
704 & 910	RDX(E)	1.248	69.1	0.96	-	55-60	11-17	-	6.65 6.88	0.04 0.06	Class E RDX (See Ref. 7)
707	Model[a]	1.105	57.3	-	-	161	-	-	∿4.9	-	Triggered on 6th probe[f]
816	M-7[b]	1.10	67.5	0.54	1.3	170 ± 5	124	91	4.89	0.21	
1513	c	1.135	69.5	-	-	F	-	-			IPs discharged randomly[f]
FKM*	d	∿1.28	70	∿0.5	-	103	76	-	5.80		Interpolated values; detailed data will be reported in subsequent TRs.[f]
VLU*	e	∿1.32	70	∿0.2	-	146	247	-	5.85		

a. Mechanical mixture 25/5/20/50 NC/AP/Aℓ/HMX
b. Shredded double-base propellant: 58.7/32.0/8.0/0.8/0.5, NC/NG/KP/EC/C
c. Shredded propellant 84.8/15.2 HMX/HTPB, Arcadene
d. Composite of HMX, AP, Aℓ and high energy binder, ρ_V = 1.83 g/cm^3.
e. CMDB Propellant containing NC, NG, Aℓ, AP, and HMX; the latter is twice the amount in FKM, ρ_V = 1.88 g/cm^3.
f. Random and erratic discharge of earlier pins.
*Powdered

compression front is formed near the ignition region; it travels at 0.8 mm/μs (local sound speed) and marks the beginning of accelerated burning which subsequently leads to the onset of detonation. In this case, there is a rearward traveling shock which originates near the region of onset.

The effect of adding Aℓ to RDX was to modify the transitional process; it increased ℓ and Δt_D. This confirms the trends found with 90% TMD HMX/Aℓ[6]. Earlier we found that the DDT results for pure RDX and pure HMX as well as those for waxed HMX and waxed RDX are quantitatively the same at comparable %TMD, particle size, and composition[7]. Here, by comparison with aluminized HMX[6], we see the same equivalence in the aluminized mixtures. In addition, we find little or no difference in detonation velocity D for 9 and 20% Aℓ at 90% TMD (also true in HMX mixes)[6], no significant difference in ℓ at 70 and 90% TMD, but a marked decrease in Δt_D as the %TMD increases from 70 to 90%.

The third group of charges consisted of NC, binary NC mixtures, and a fine HMX/AP mixture. These combinations would be expected in CMDB propellants. Records for the NC at 60 and 69% TMD (Figs. A8 and A10) are very similar to that of 80/20 RDX/Aℓ at 70% TMD without the rearward traveling shock; they follow the same physical model. Again, increasing the %TMD did not change the ℓ value but appreciably decreased the relative time to detonation Δt_D and decreased somewhat the time between formation of the first compression front and the onset of detonation, Δt_F. Addition of 20% Aℓ to the NC resulted in a failure to transit. Hence Aℓ hindered DDT in NC mixtures as well as in RDX mixes. On the other hand, addition of 15% AP to NC enhanced the transitional process*, i.e., reduced both ℓ and Δt_D. (No shot was made on 15μ HMX, but the values should be the same as those obtained for 15μ RDX; the latter values from Reference 7 are given for comparison in Table 1.)

The final group of charges consisted of a four-component model, a double-base gun propellant, and a plastic bonded HMX used as a gas generator. We also have for comparison, interpolated data on FKM[8], a composite rocket propellant, and VLU, a CMDB rocket propellant[9].

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[6] Price, D. and Clairmont, A. R., Jr., "Deflagration to Detonation Transition Behavior of Aluminized HMX," NSWC TR 79-119, Jun 1979.

[7] Price, D. and Bernecker, R. R., "DDT Behavior of Waxed Mixtures of RDX, HMX, and Tetryl," NSWC/WOL TR 77-96, Oct 1977.

[8] Bernecker, R. R. and Price, D., unpublished data.

[9] Bernecker, R. R., Price, D., and Sandusky, H., "Burning to Detonation Transition in Porous Beds of High Energy Propellant," NSWC TR 79-351, Nov 1979.

*Note the very high IP front velocity here, again indicative of the ease of onset of convective burning of AP mixtures.

The model, which was 25/5/20/50 NC/AP/Aℓ/HMX, was at 57.3% TMD; its firing resulted in an unexpected phenomenon -- the random and erratic discharge of the first five IPs. By the time the 6th-10th pins responded in their normal sequence, the material was already detonating. In previous work, we have encountered this experimental difficulty only in coarse tetryl at high porosity[10]. As the porosity was decreased in the tetryl, the problem disappeared. It is highly probable that the problem would be less serious if the model were examined at lower porosities. However, the problem is quite evident at 57% TMD, and, as in the case of tetryl, must be attributed to low pressure reaction producing products of such low electrical conductivity that the IPs fail to respond to them.

Since the detonation velocity of this model was unknown, separate unconfined charges of 15.9 mm dia. were shock initiated. D, measured by probes, was

Shot	ρ_o, g/cm^3	%TMD	D, mm/μs
D-1009	1.096	57.1	4.84
D-1010	1.092	56.9	4.74

Since D in Shot 707 was about 4.9 mm/μs, there is no doubt that this material did achieve detonation in the transition experiment.

All possible pairs of components in this model have been examined (at least at a single ratio of contents) except NC/HMX, and these two materials have been studied separately. The only combination in which the results suggested a slight difficulty in IP response was NC/Aℓ. Although the early IPs did not show erratic discharge, the probe record was not triggered until the third probe.

The random and erratic discharge of the early IPs suggested that different probes were discharged by different fronts instead of the customary sequential discharge by a single (the first) ionic front. SG records which recorded for only 500 μsec showed very low pressures at all locations, but one oscilloscope set to record for 700 μsec showed a rapid pressure rise at the 21 and 131 mm locations at about 580 μs (See Fig. A13b). These results suggest a longer burning time at lower pressure and a much sharper subsequent pressure rise than we have seen in most organic HE. The DDT mechanism might well be different from that of the proposed physical model.

The shredded gun propellant M-7 (67.5% TMD) showed a normal DDT record (Fig. A14) indicating that its transitional mechanism was that of the proposed physical model. Shredded Arcadene failed to transit and, at 70% TMD, produced random discharge of IPs. No records are shown here for FKM or VLU, but the latter, which contained NC and Aℓ exhibited random and erratic discharge of the

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[10] Price, D., Bernecker, R. R., Erkman, J. O., and Clairmont, A. R., Jr., "DDT Behavior of Tetryl and Picric Acid," NSWC/WOL TR 76-31, May 1976.

IPs. The three 70% TMD propellants which showed DDT had a range in ℓ of 103-170 mm and in Δt_D of 76-247 μs.

SUMMARY AND CONCLUSIONS

1. 80/20 AP/fuel does not exhibit DDT at 57-67% TMD in the present setup. Fuels examined were wax and Aℓ.

2. Addition of Aℓ to RDX increases ℓ and Δt at both 70 and 90% TMD. Results at 90% TMD essentially duplicate those of comparable HMX/Aℓ compositions. Decrease of porosity from 30 to 10% did not affect ℓ of RDX/Aℓ, but did decrease Δt_D.

3. NC exhibited DDT at 60 and 69% TMD with the same ℓ value at each porosity; Δt_D at 69% TMD was distinctly less than Δt_D at the greater porosity. Addition of Aℓ to NC hindered transition whereas addition of AP enhanced it. Addition of AP to HMX, however, interfered with the transition.

4. The 4-component model and two different propellants exhibited random and erratic discharge of IPs at 30-43% porosity. Additional instrumentation is therefore necessary for studying some propellants at high porosity.

5. Propellants which showed a transition at 70% TMD in our apparatus, had a range of ℓ of 103-170 mm and in Δt_D of 76-247 μs.

6. All transitions for which complete records were obtained seemed to follow the mechanism of the original model.

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3. Price, D., Clairmont, A. R., Jr., and Erkman, J. O., "Explosive Behavior of Aluminized Ammonium Perchlorate," Combust. Flame, Vol. 20, 1973, 389-400.

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APPENDIX A

DETAILED DISCUSSION OF RECORDED DATA

In previous work we have presented results from each shot as a composite illustration of distance-time and strain-time data. Here we shall follow the same scheme insofar as possible. However, in contrast to earlier work, we have examined here a large variety of 60-70% TMD charges, not a series with regular composition or compaction changes such as RDX/wax[1]. As a result of unpredictable variations in the DDT behavior of the present collection of charges, a number of SG records were triggered too late to give any information about predetonation conditions. Addition of aluminum to these porous charges has increased the "hash" on SG records (some hash, caused by interactions from discharge of the IPs, is always present.) When the SG record was illegible or contributed but a single point, its trace was not reproduced. The single point, which was read directly from the original polaroid record, was recorded in the table of detailed data.

The established procedure for determining the predetonation column length ℓ is from the wall markings; this is then checked for consistency with the IP data in the distance-time plot. In the present results, there were three cases in which ℓ could not be determined from fragment markings. In two cases, the probe data supplied an acceptable value, but in one case (that marked with an asterisk in Table A1) there was an ambiguity.

Table A1 contains the measured and assigned ℓ values. Table A2 shows the rest of the detailed data for each shot.

Figs. A1-A3 show the x-t plots for three binary AP mixtures at 57-67% TMD. None exhibited transition to detonation, and all burned. The fronts outlined by the probe discharges (IP fronts) showed velocities of 0.6-0.8 mm/μs, high for convective fronts at this high porosity. (Fig. A1 suggests that in the case of 67% TMD 80/20 AP/wax the IP front might be caused by a pressure induced reaction. In neither of the 57% TMD charges was a similar leading pressure front detected.) Moreover, the velocity of the IP fronts in Figs. A1 and A2 appears to increase with decreasing % TMD, a trend opposite to that shown by the convective front in waxed RDX. Neither 20% Aℓ nor 20% wax added to AP was sufficient to effect DDT in our apparatus. The IP fronts were almost identical in 80/20 AP/wax and 80/20 AP/Aℓ, but the following compressive fronts indicated greater reaction in the ignitor region for the former.

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[1] Bernecker, R. R. and Price, D., "Studies in the Transition from Deflagration to Detonation in Granular Explosives," Combust. Flame, Vol. 22, 1974, 111-117, 119-129, and 161-170. See also NOLTR 72-202.

The next four charges are aluminized RDX at 90 and 70% TMD; all exhibited DDT. The lightly aluminized (9%) charges transited so rapidly that SG records triggered by the IP at 41 mm, showed nothing (e.g., Fig. A4) or merely a response to the detonation wave (e.g., Fig. A5). In Fig. A4 only data from the last six probes (commercial) have been used to calculate the detonation velocity. Although the WOL and commercial probes measure exactly the same detonation velocities, the former do respond slightly earlier than the latter. In this particular case, it seems preferable not to mix the two sets of data.

Addition of 9% Aℓ to RDX at 70% has increased ℓ and Δt_D (for RDX, the values are, respectively, 40-45 mm and 0-5 μs[7]); this may also be true at 90% TMD where the values of Table A2 or Table 1 of the text can be compared to extrapolated values for HMX (45 mm and 10 μs[6]), but the difference in Δt_D is too small to be significant. The values of ℓ are, within experimental error, the same for the 70% and 90% TMD charges and so too are the values of Δt_D.

In Fig. A6a, the assigned ℓ value of 92 ±10 mm is shown. This was a case in which ℓ could not be determined from tube fragments, and its choice from the probe data was not clear-cut. For example, the response of the probe just before onset of detonation is frequently, although not always, delayed. Consequently, we used the practically identical behavior of HMX and RDX, and assigned the value obtained in 90% TMD 80/20 HMX/Aℓ[6]. All values are for Class A HE, i.e. $\bar{\delta} \sim 200\mu$, and H-5 Aℓ. The assumed equivalence of RDX and HMX also seems justified by the close agreement of the DDT parameters:

H.E.	9-10% Aℓ at 90% TMD	
	ℓ, mm	$^{41}\Delta t_D$ μs
RDX	59	7.1
HMX	56	5.6
	20% Aℓ at 90% TMD	
RDX	(92)	25
HMX	92	23

It is evident that at 90% TMD increasing the Aℓ content from 9 to 20% has increased ℓ and Δt_D.

[6] Price, D. and Clairmont, A. R., Jr., "Deflagration to Detonation Transition Behavior of Aluminized HMX," NSWC TR 79-119, Jun 1979.

[7] Price, D. and Bernecker, R. R., "DDT Behavior of Waxed Mixtures of RDX, HMX, and Tetryl," NSWC/WOL TR 77-96, Oct 1977.

Fig. A7 displays the data for 70% TMD 80/20 RDX/Aℓ. This figure shows the most complete data sets for this series of compositions. The initial IP front at 0.26 mm/μs is quite probably a convective wave. It is followed by a compressive wave at 0.8 mm/μs, a reasonable rate for 30% porous material, and that, in turn, by the onset of detonation at a rate 20% less than the ideal value for non-aluminized RDX. A shock traveling rearward from the region of onset is also evident. In other words, this transition follows exactly that proposed for waxed RDX[1]. It is probable that better time resolution would also demonstrate the same mechanism in the other HE/Aℓ charges of this series.

As was the case for 91/9 RDX/Aℓ, the initial charge compaction of the 80/20 RDX/Aℓ had no experimentally significant effect on the value of ℓ. However, it had a very large effect on the relative time Δt_D; it showed that relative time to detonation decreases as %TMD increases. The same direction of change was indicated by the 91/9 RDX/Aℓ although 2 μs (from 9 to 7) is not a significant difference (i.e., it is well within our experimental error).

Fig. A8 contains the data obtained on 59.9% TMD NC (Ball Powder). Fig. A8a shows that this material clearly follows the original physical model. Both the convective and postconvective fronts exhibit the appropriate velocity values for the high porosity. They also intersect about 26 mm and 25 μs before the onset of detonation. Additional information is that the first SG (x=20.1 mm) shows an excursion that might indicate a rearward traveling compression wave from 20<x<67 mm or might indicate some disturbance of the gage output near the ignitor region. The last SG (x=168.7 mm) was located near the onset of detonation and responds to that event. In Fig. A8b, the record of the SG at 67 mm shows a distorted plateau, starting at about 280 μs. If a retonation or a shock wave traveled from the onset of detonation to this SG at 4.81 mm/μs (the measured D), it would reach x=67 at 277 μs. Hence the plateau might have been caused by such a shock. The larger peak, which follows the plateau, begins at 303 μs. A compression wave from x=ℓ=163 mm would have to travel at 2.1 mm/ s to arrive at that time. However, at both 277 and 303 μs, the strain at x=67 is well above that for the yield point of the tube. Hence both details may be artifacts of the tube's plastic deformation.

Fig. A9 portrays the records from a charge of approximately the same porosity; it is NC to which 20% ∿5μ Aℓ has been added. As Fig. A9a shows, both a convective front and a postconvective front are formed shortly after ignition. However, the pressure remains low (See Fig. A9b), and the strain does not increase rapidly to exceed the yield point until about 500 μs (about 150 μs after the end of the probe records). At that time, the tube probably underwent a pressure burst. Thus addition of aluminum to NC decreases its ability to undergo DDT. This was also the case for RDX above, where, however, Aℓ delayed but did not prevent DDT. Finally, note that the first two probes did not respond to the early NC/Aℓ reaction. Recording was triggered by the third probe.

Because most of our exploratory work was done at 70% TMD, NC was mechanically compacted to about this value. Fig. A10 displays the data which show a very similar DDT behavior to that of ∿60% TMD. The details which have changed are those to be expected with a more rapid transition to detonation: front velocities are higher, intersection of the convective and postconvective fronts earlier, and the relative times (Δt_D, Δt_E) have decreased.. On the other hand, the predetonation column length ℓ has been unaffected by increasing the compaction from 60 to 70% TMD.

The previous plot for NC can be compared to that of Fig. A11 for 85/15 NC/AP. Addition of 15% ammonium perchlorate has so decreased the time required for transition that at x=41 mm, the IP front is already traveling at 1.8 mm/μs, and the onset of detonation occurs at 63 mm. Since the SGs, triggered by the first IP, start recording late in the transitional process, only one excursion appeared and that one was a response to the detonation. Thus addition of AP to NC, decreased ℓ and Δt_D, and had a negligible effect on D.

The effect of adding AP to a fine ($\delta \sim 15\mu$) HMX was explored with a 91/9 HMX/AP mixture (see Fig. A12). It is not surprising that the reaction is again rapid and that SGs recorded little data of value. By comparison with results obtained with fine RDX[7], it appears that addition of AP to HMX increases both ℓ and Δt_D. In other words, AP decreases the tendency of HMX to undergo DDT; it has also reduced D by 8.5% below its ideal value at this %TMD.

Fig. A13 displays the data from the shot on a 57.3% TMD mixture of NC/AP/Aℓ/HMX. In this material there was an early reaction causing random and erratic discharge of the earlier IPs. As a result the oscilloscopes for the SGs were triggered some time before the last half of the IP series which gave the D value of Fig. A13a. SGs on the oscilloscope with a sweep of about 470 μs showed essentially no pressure change as also did those of Fig. A13b which fed into an oscilloscope set for a longer sweep. Since thepressure did not change for the first 470 μs of recording, the plot of Fig. A13b started at ~460 μs. The curves for the 20.8 mm and 130.7 mm locations cross, and indicate a rearward traveling shock. From the time of the pressure excursions and the separation distance, the velocity is 3.5 mm/μs. If this shock originates at the time and location of the onset of detonation (Fig. A13a) and travels at this constant velocity, then 541 μs on Fig. A13b would correspond to time zero on Fig. A13a. This is the only shot included in this report for which the SG and IP records had different zero times.

There is no question that this model underwent a transition to detonation. The wall markings and the IP data clearly show this. However, the tube damage was much less than might be expected, less for instance than that for Shot 810 on NC at 59.9% TMD. A length of about 3.7 in. tube at the ignitor end was intact after the shot with the mix. It is possible that the observed DDT was of the explosive components, (e.g., HMX and NC) at high porosity, rather than the detonation of the entire mix as a composite explosive

A modified M-7 gun propellant, 58.7/32.0/8.0/0.8/0.5 NC/NG/KP/EC/C, was shredded by cutting thin slices with a razor. The shreds were compacted to 67.5% TMD in a DDT tube in which the charge was subsequently fired. Fig. A14 shows the resultant data. As the figures show, this propellant follows the usual path for DDT. Since it was pressed to nearly 70% TMD rather than the ~60% TMD of the previous charge, it showed much more fracture damage of the containing tube.

TABLE A1

MEASURED AND ASSIGNED ℓ VALUES

			ℓ Values, mm		
Shot No.	Material	%TMD	From x-t Plot	From wall Markings	Assigned
805	80/20 AP/Wax	67.0			
809	"	56.6			
906	80/20 AP/Aℓ	56.8			
1012	91/9 RDX/Aℓ	89.6	60^{+5}_{-2}	59.2±2	59±2
1109	"	71.2	57^{+3}_{-0}	54.1	58±2
1118	80/20 RDX/Aℓ	89.8	75±5	>59	92±10*
1203	80/20 "	70.4	85^{+3}_{-0}	87.1±3	87±3
810	NC	59.9	165^{+5}_{-0}	163.3±3	163±3
905	80/20 NC/Aℓ	57.0	-	-	F
1101	NC	69.4	165	165±3	165±3
1008	85/15 NC/AP	69.8	60^{+5}_{-0}	63±2	63±2
1005	91/9 HMX(E)/AP	69.5	85^{+5}_{-0}	54<ℓ<181	86±2
707	4C Model		-	161±3	161±3
816	M-7		170±5	-	170±5
1515	Arcadene		-	-	F

*See text

TABLE A2 DETAILED DATA FOR DDT EXPERIMENTS WITH VARIOUS MATERIALS

Shot No.	805		809		906		1012	
Material:	80/20 AP/Wax		80/20 AP/Wax		80/20 AP/Aℓ		91/9 RDX/Aℓ	
Density $\rho_0(\rho_v)$g/cm^3	1.10 (1.64)		0.93 (1.64)		1.17 (2.06)		1.667 (1.861)	
%TMD	67.0		56.6		56.8		89.6	
IP Data	x	t	x	t	x	t	x	t
	41.4**	0.0*	41.4	0.0*	41.5	Blanked	41.5	0.0*
	54.1	19.7*	54.1	11.6*	60.6	"	60.6	7.35*
	79.6	57.8*	79.5	55.1*	79.6	0.0	79.6	9.63*
	104.9	89.3*	104.9	86.9*	105.0	Blanked	105.0	12.88*
	130.3	134.2*	130.3	130.5*	130.4	63.6	124.1	15.70*
	155.8	171.5*	155.7	160.4*	155.8	94.6	143.1	19.24
	181.2	214.7*	181.2	193.7*	181.4	134.9	162.3	21.70
	206.6	261.4*	206.6	227.5*	200.4	-	181.4	23.26
	232.0	300.8*	232.0	261.5*	219.5	183.4	206.8	27.34
	257.3	346.6*	257.3	291.7*	238.5	212.6	232.2	29.96
					257.6	242.1	263.9	35.35
SG Data	20.3	-	20.1	-	22.9	-	SG records triggered too late to show any predetonation detail. Unread.	
	67.7	29.5	66.4	54.5	67.1	-		
	92.5	63.6	92.3	84.6	92.1	26.9		
	118.0	87.5	117.6	136.4	117.7	80.0		
	143.3	-	155.8	-	155.8	-		
Predet. vel, mm/μs	0.64 - 0.58 1.0		0.73 0.63		0.8 - 0.7 0.5		2.6	
ℓ(mm)	F		F		F		59	
$^{41}\Delta t_D$(μs)	-		-		-		7.1	
$^{41}\Delta t_E$(μs)	-		-		-		-	
D(σ) mm/μs	-		-		-		7.29(0.14)	

*Custom-made probes **NC on tip

TABLE A2 (Cont.) DETAILED DATA FOR DDT EXPERIMENTS WITH VARIOUS MATERIALS

Shot No.	1109		1118		1203		810	
Material:	91/9 RDX/Aℓ		80/20 RDX/Aℓ		80/20 RDX/Wax		NC	
Density $\rho_o(\rho_v)$g/cm^3	1.324 (1.861)		1.734 (1.934)		1.359 (1.934)		0.947 (1.58)	
%TMD	71.2		89.8		70.4		59.9	
IP Data	x	t	x	t	x	t	x	t
	41.5	0.0*	41.5	0.0*	41.4	0.0*	41.4	0.0*
	54.12	7.50*	60.5	19.3*	66.9	96.3*	54.2	34.6*
	66.9	10.55*	79.5	24.0*	92.2	174.7*	79.5	94.8*
	79.6	12.3*	104.9	26.7*	117.6	179.35*	104.9	153.4*
	105.0	16.5*	130.4	30.4	143.0	183.7*	130.3	217.1*
	130.4	20.25*	155.8	33.9	168.4	187.7*	155.8	247.25*
	155.7	24.1*	181.1	36.55	187.5	192.3	181.2	260.8*
	181.4	28.0*	206.5	39.4	206.6	195.65	206.6	266.25*
	206.6	32.0*	225.7	41.95	225.6	198.5	232.0	272.2*
	232.0	36.05*	244.7	44.35	244.6	202.0	257.4	276.35*
	257.4	37.55*?	263.8	47.1	263.7	205.35		
SG Data	20.6	-	20.7	-	20.6	100,185	20.1	143,220
	60.8	8.9	67.1	21.1	54.2	138,182	67.2	145-6,280
	79.8	-	86.1	-	73.4	164,172.7-176.5	104.8	194
	105.2	-	105.0	-			136.9	232
	124.2	-	130.4	-			168.7	248,257
Predet. vel., mm/μs	1.7		0.98		0.26-0.32 0.81		0.37-0.40 0.80	
ℓ(mm)	58		92		87		163	
$^{41}\Delta t_D$(μs)	9.0		25.0		173		257	
$^{41}\Delta t_E$(μs)			-		49		141	
D(σ) mm/μs	6.48(0.03)		∿7.8		5.56(0.07)		4.81(0.24)	

*Custom-made probes

TABLE A2 (Cont.) DETAILED DATA FOR DDT EXPERIMENTS WITH VARIOUS MATERIALS

Shot No.	905		1101		1008		1005	
Material:	80/20 NC/Aℓ		NC		85/15 NC/AP		91/9 HMX(E)/AP	
Density $\rho_o(\rho_v)$g/cm^3	0.980(1.72)		1.097(1.58)		1.135(1.63)		1.324(1.90)	
%TMD	57.0		69.4		69.8		69.5	
IP Data	x	t	x	t	x	t	x	t
	41.5	-*	41.8	0.0*	41.5	0.0*	41.4	0.0*
	60.6	-*	60.8	34.8*	60.6	10.90*	60.6	19.6*
	79.6	0.0*	79.9	66.5*	79.8	14.44*	79.6	33.3*
	105.0	76.3*	105.3	99.0*	105.2	18.59*	105.2	39.0*
	130.6	148.9*	130.7	120.1*	130.4	22.73*	130.6	41.4
	156.0	195.7*	149.6	134.6*	143.1	25.89*	155.8	46.0
	181.4	234.9*	168.8	145.8*	168.7	30.49*	174.9	48.9
	200.3	264.9*	187.8	149.05*	187.7	33.04*	194.1	52.1
	219.5	292.9*	206.9	-	206.6	36.55*	213.1	54.3
	238.5	319.3*	232.15	157.7*	232.2	40.65*	232.2	57.5
	257.6	345.3*	257.8	161.7*	257.7	45.69*	257.6	62.0
SG Data	20.3	-	20.5	80	20.7	-	20.6	-
	66.8	83	67.1	55	79.8	15.6	79.8	26
	105.3	115,144	92.7	73	104.9		105.4	
	136.4	182	118.2	97	130.3	Illegible	143.1	Illegible
	168.5	-			155.8		181.2	
Predet. vel. mm/μs	0.34 - 0.63		0.55 - 1.3		1.8		0.98 - 1.4	
	0.71		1.2		-		-	
ℓ(mm)	F		165		63		86	
$^{41}\Delta t_D$			145		11.3		35.5	
$^{41}\Delta t_E$			105		-		-	
D(σ) mm/μs			5.49(0.16)		5.70(0.06)		6.53(0.16)	

*Custom-made probes

TABLE A2 (Cont.) DETAILED DATA FOR DDT EXPERIMENTS WITH VARIOUS MATERIALS

Shot No.	707		816		1513	
Material:	4 Comp. model[a]		M-7[b]		84.8/15.2 HMX/HTPB[c]	
Density $\rho_0(\rho_v)$g/cm^3	1.105(1.92)		1.10(1.63)		1.135(1.634)	
%TMD	57.3		67.5		69.5	
IP Data	x	t	x	t	x	t
	28.70	-*	41.4	0.0*	Erratic discharge of some IPs	
	54.10	-*	54.1	25.6*	over period of ~1ms. All	
	79.50	-*	79.6	70.45*	material burned.	
	104.90	-*	105.0	90.35*		
	130.30	-*	130.3	111.05*		
	155.70	0	155.7	119.10*		
	181.23	5.08*	181.2	125.45*		
	206.63	10.93	206.6	131.10*		
	232.03	15.86	231.9	136.55*		
	257.43	20.82	257.3	140.85*		
SG Data	20.8	510,581[d]	20.8	-	Low pressures and low	
	54.4	-	67.1	53	buildup rates	
	80.3	-	105.4	79		
	104.9	-	136.9	105		
	130.7	550	168.8	-		
Predeton. vel.	-		0.50 - 1.28			
mm/μs	-		1.34		-	
ℓ(mm)	161		170		F	
$^{41}\Delta t_D$(μs)	-		124			
$^{41}\Delta t_E$(μs)	-		91			
D(σ), mm/μs	∿4.9		4.89(0.21)			

a. 25/5/20/50 NC/AP/Aℓ/HMX b. Double base powder: 58.7/32.0/8.0/0.8/0.5 NC/NG/$KClO_4$/EC/C shredded;
c. Shredded; d. Oscilloscopes triggered during random and erratic discharge of IPs prior to series recorded above; time scales differ.

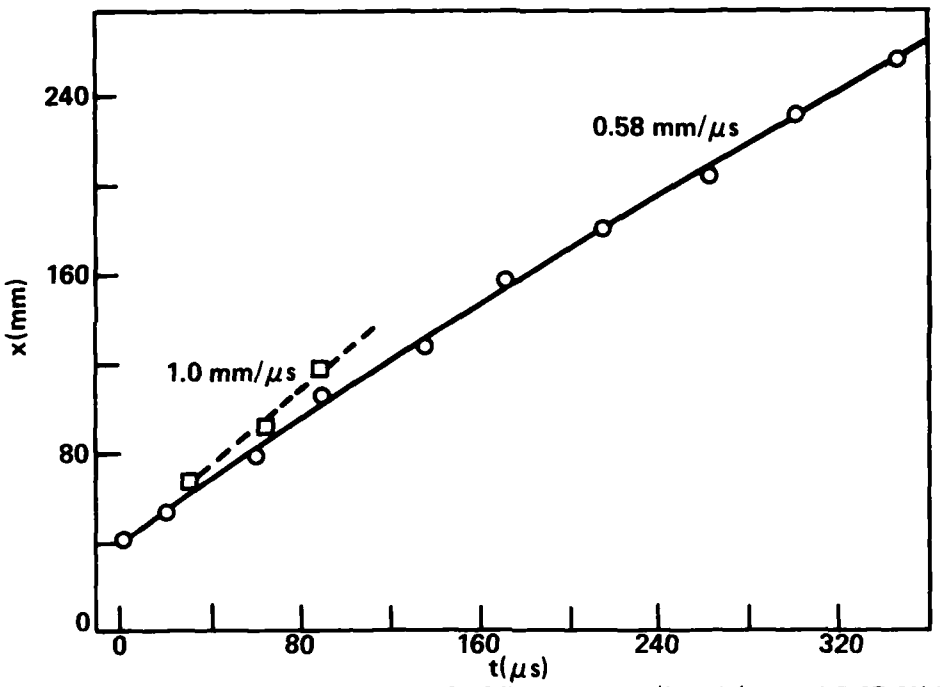


FIGURE A1 DISTANCE-TIME DATA FROM SHOT 805 ON 80/20 AP/WAX AT 67.0% TMD, ρ_o = 1.10 g/cm^3. (O WOL PROBE, ● COMMERCIAL PROBE, □ PRESSURE EXCURSION)

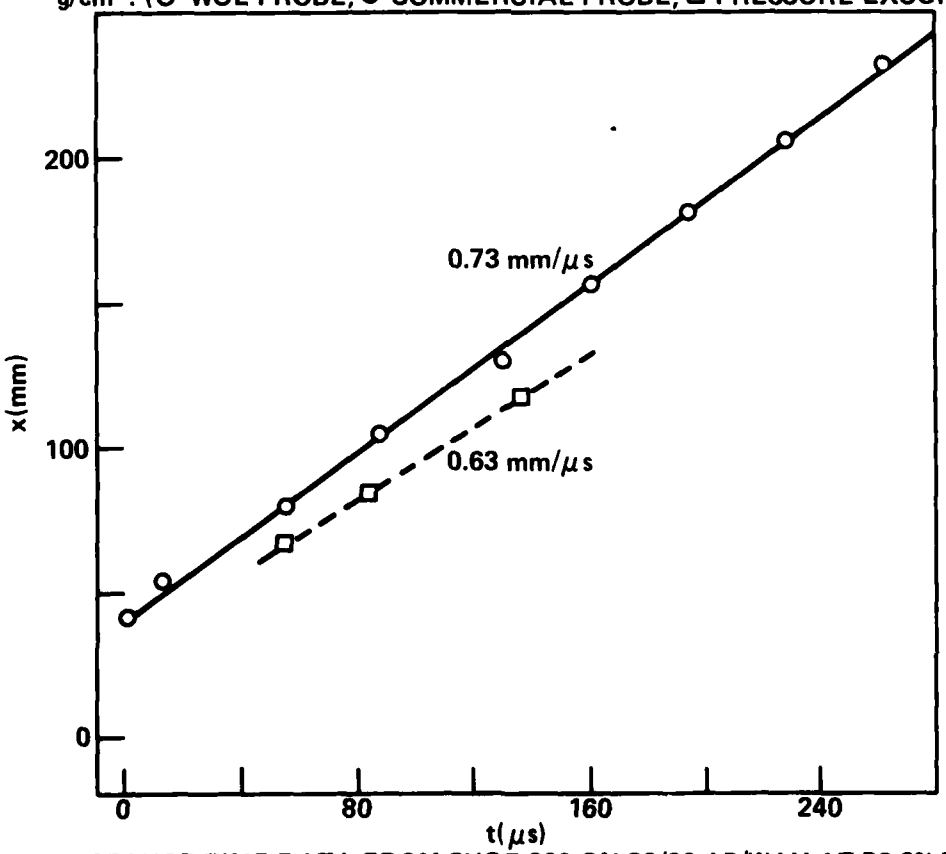


FIGURE A2 DISTANCE-TIME DATA FROM SHOT 809 ON 80/20 AP/WAX AT 56.6% TMD, ρ_o = 0.93 g/cm^3. (KEY OF FIGURE A1)

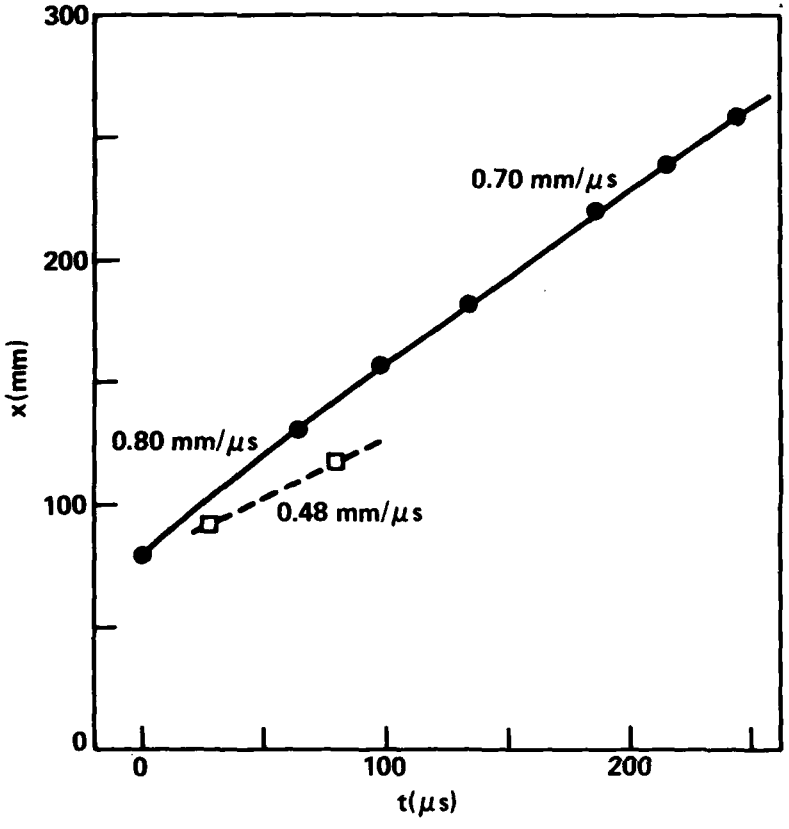


FIGURE A3 DISTANCE-TIME DATA FROM SHOT 906 ON 80/20 AP/Aℓ AT 56.8% TMD, ρ_o = 1.17 g/cm^3. (KEY OF FIGURE A1)

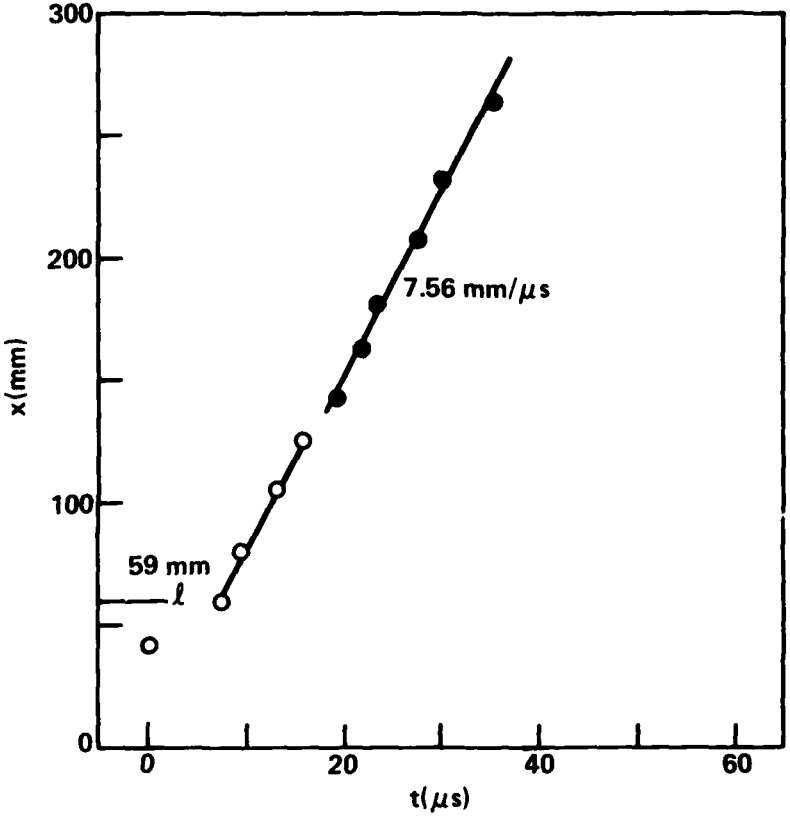
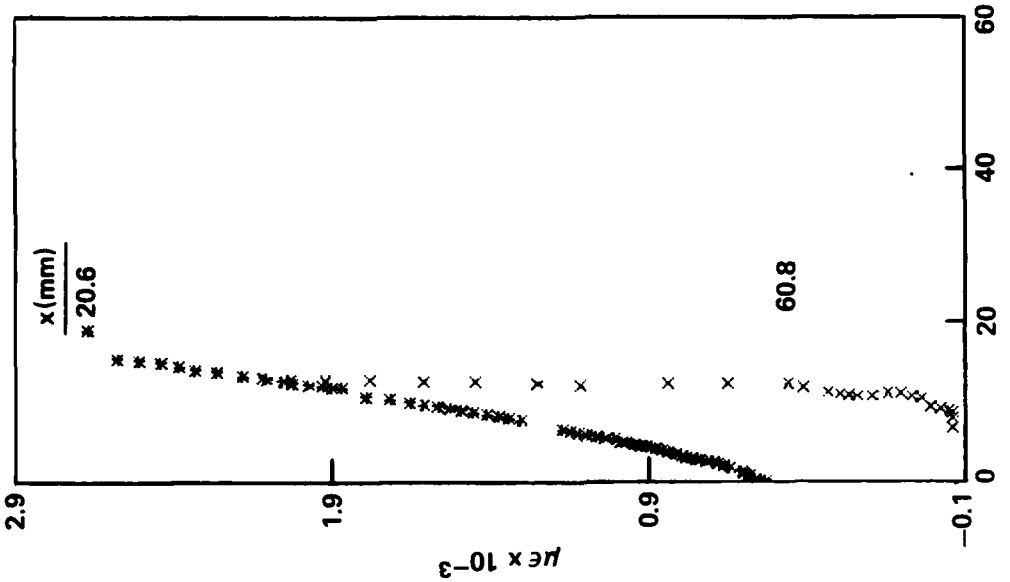
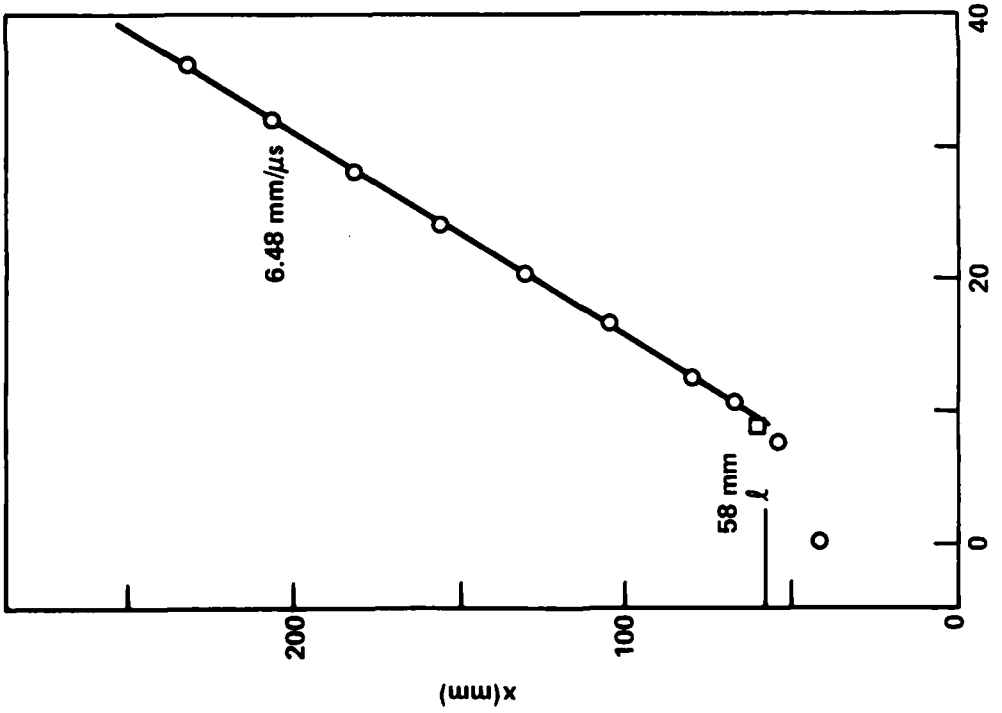


FIGURE A4 DISTANCE-TIME DATA FROM SHOT 1012 ON 91/9 RDX/Aℓ AT 89.6% TMD, ρ_o = 1.67 g/cm^3. (KEY OF FIGURE A1)

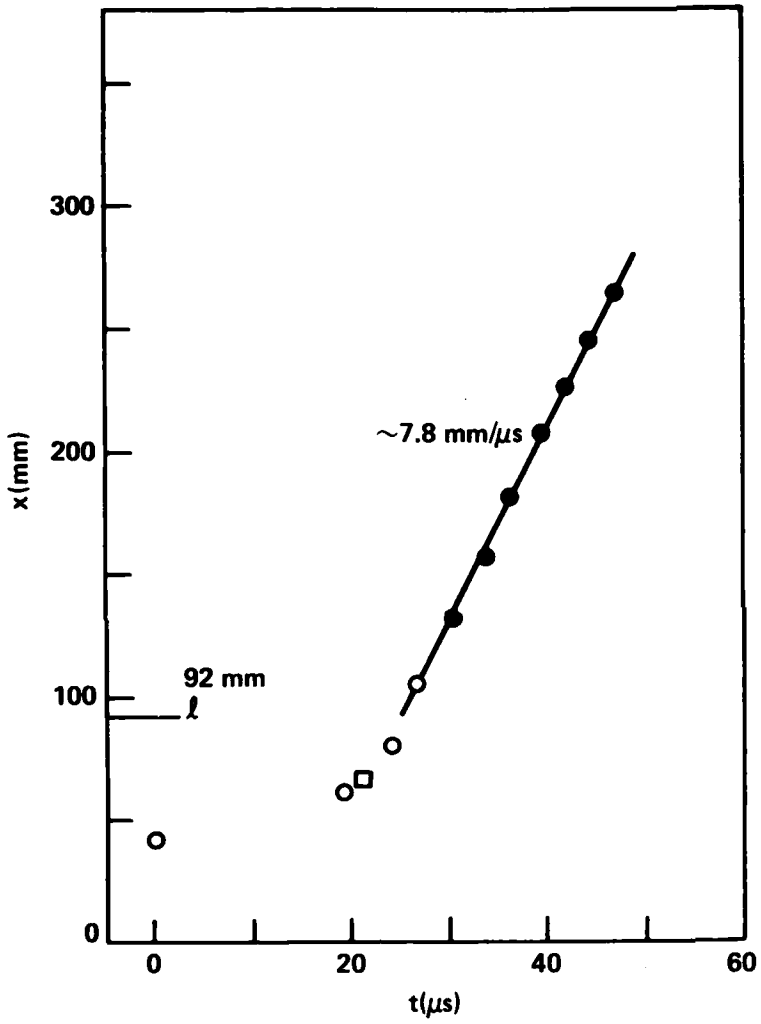


b. STRAIN-TIME DATA

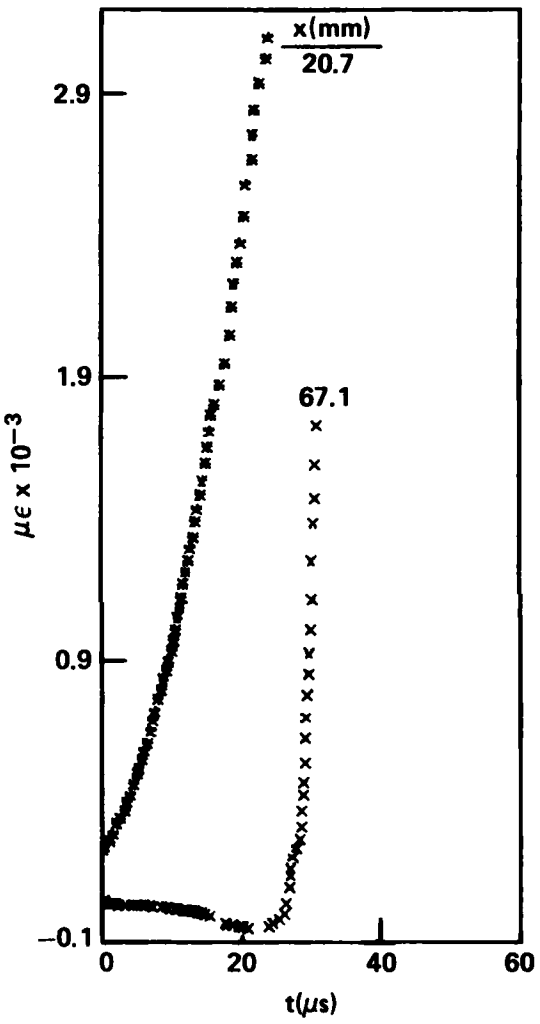


a. DISTANCE-TIME DATA (KEY OF FIGURE A1)

FIGURE A5 DATA FROM SHOT 1109 ON 91/9 RDX/Aℓ AT 71.2% TMD, ρ_o = 1.32 g/cm^3

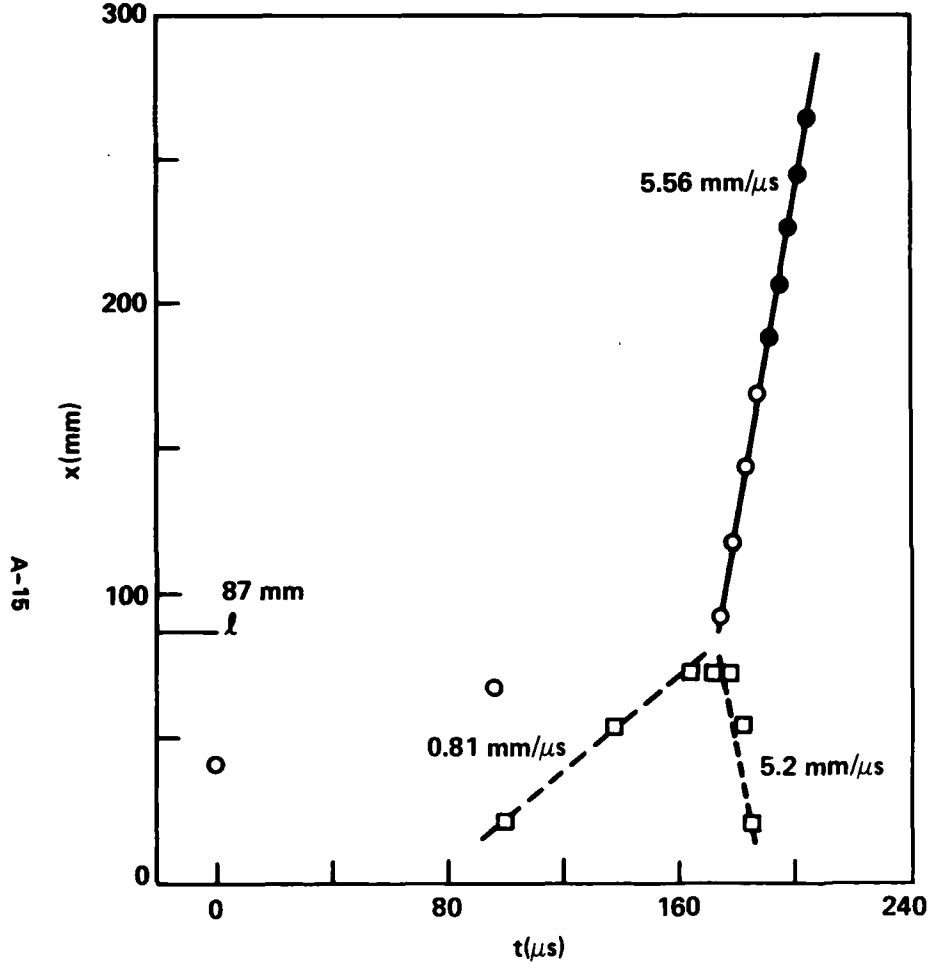


a. DISTANCE-TIME DATA (KEY OF FIGURE A1)

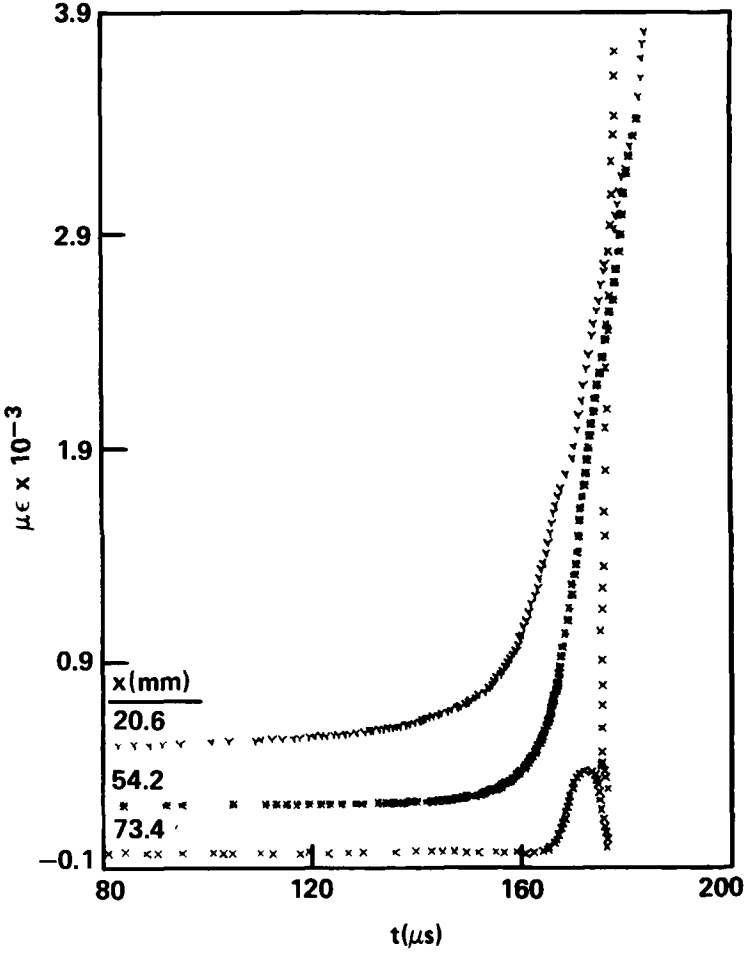


b. STRAIN-TIME DATA

FIGURE A6 DATA FROM SHOT 1118 ON 80/20 RDX/Aℓ AT 89.8% TMD, ρ_o = 1.73 g/cm^3

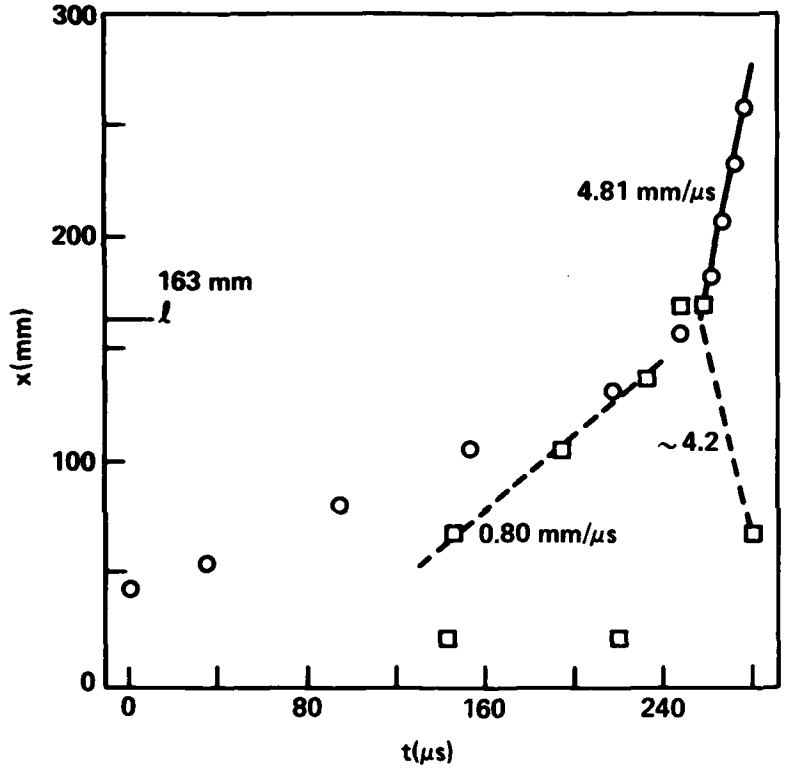


a. DISTANCE-TIME DATA (KEY OF FIGURE A1)

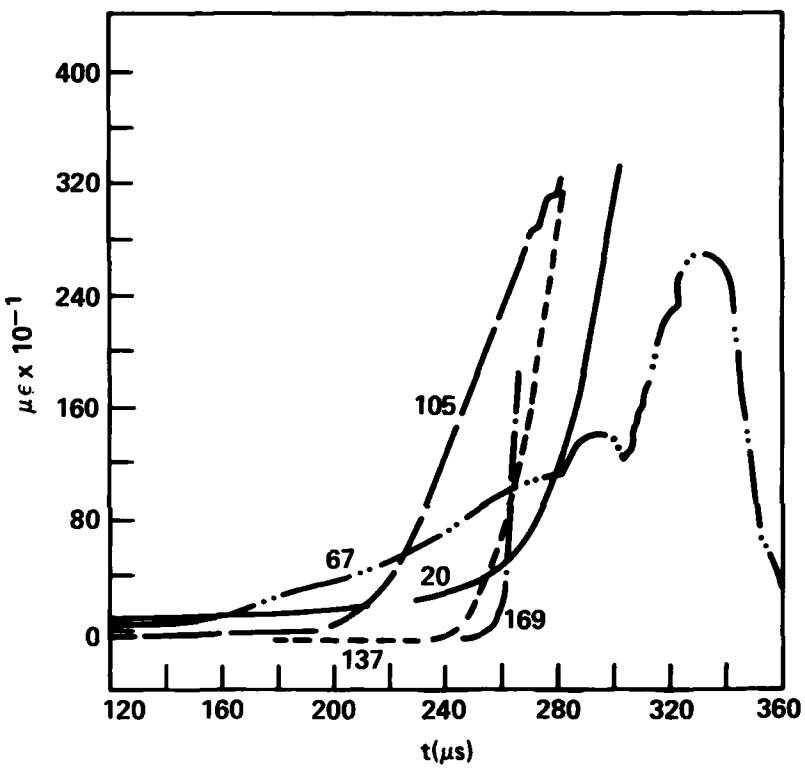


b. STRAIN-TIME DATA (EACH CURVE, EXCEPT THE LOWEST, HAS BEEN RAISED 200με – OR AN INTEGRAL MULTIPLE THEREOF – FOR BETTER DATA DISPLAY)

FIGURE A7 DATA FROM SHOT 1203 ON 80/20 RDX/Aℓ AT 70.4% TMD, ρ_o = 1.36 g/cm^3

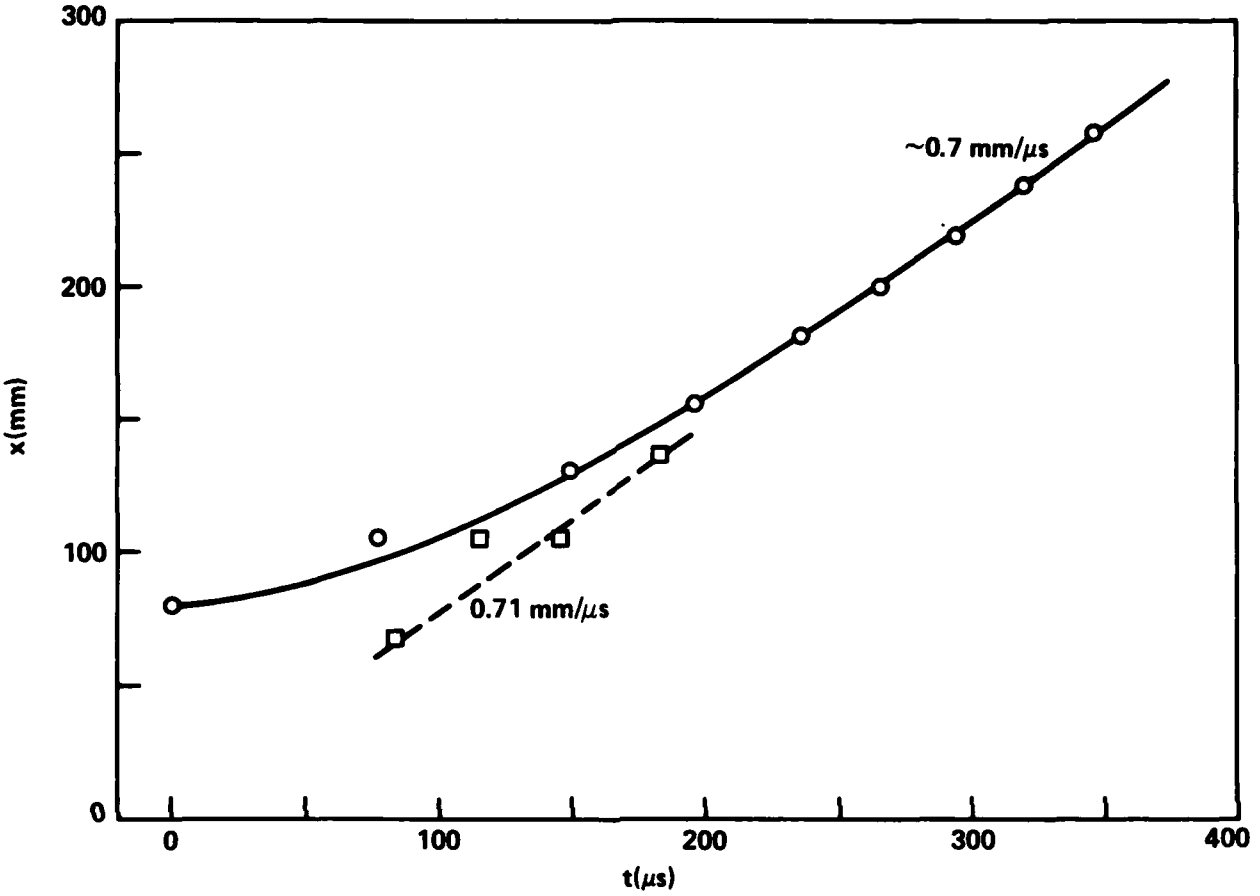


a. DISTANCE-TIME DATA (KEY OF FIGURE A1)

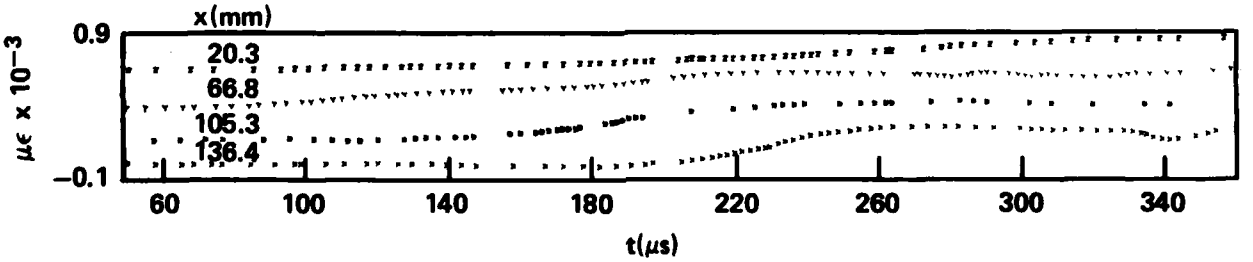


b. STRAIN-TIME DATA

FIGURE A8 DATA FROM SHOT 810 ON NC AT 59.9% TMD, ρ_o = 0.95 g/cm^3

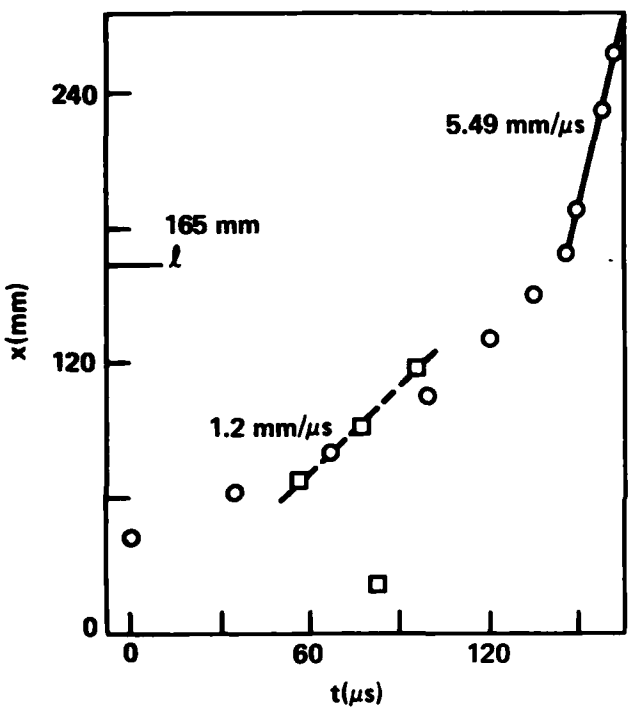


a. DISTANCE-TIME DATA (KEY OF FIGURE A1)

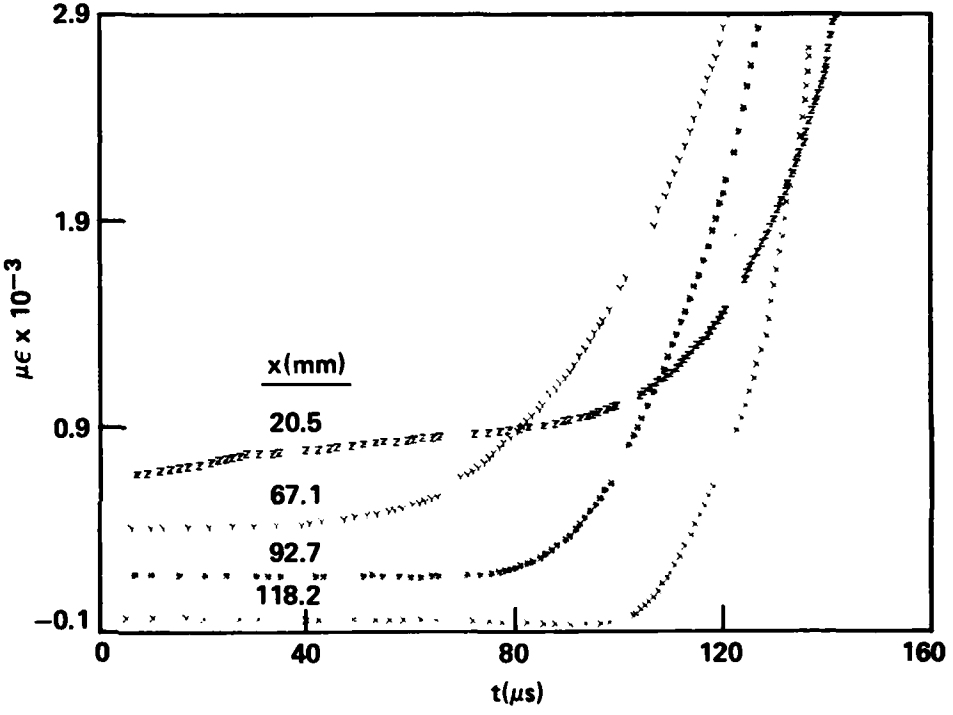


b. STRAIN-TIME DATA (KEY OF FIGURE A7b)

FIGURE A9 DATA FROM SHOT 905 ON 80/20 NC/Aℓ AT 57.0% TMD, ρ_o = 0.98 g/cm^3



a. DISTANCE-TIME DATA (KEY OF FIGURE A1)



b. STRAIN-TIME DATA (KEY OF FIGURE A7b)

FIGURE A10 DATA FROM SHOT 1101 ON NC AT 69.4% TMD, ρ_o = 1.10 g/cm^3

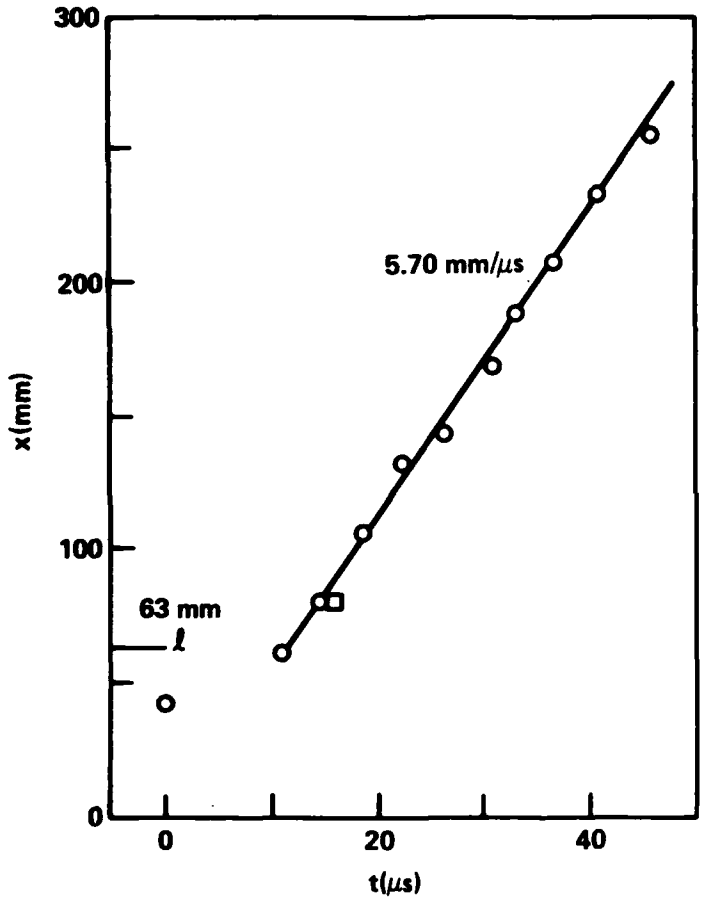


FIGURE A11 DISTANCE-TIME DATA FROM SHOT 1008 ON 85/15 NC/AP AT 69.8% TMD, ρ_o = 1.14 g/cm^3. (KEY OF FIGURE A1)

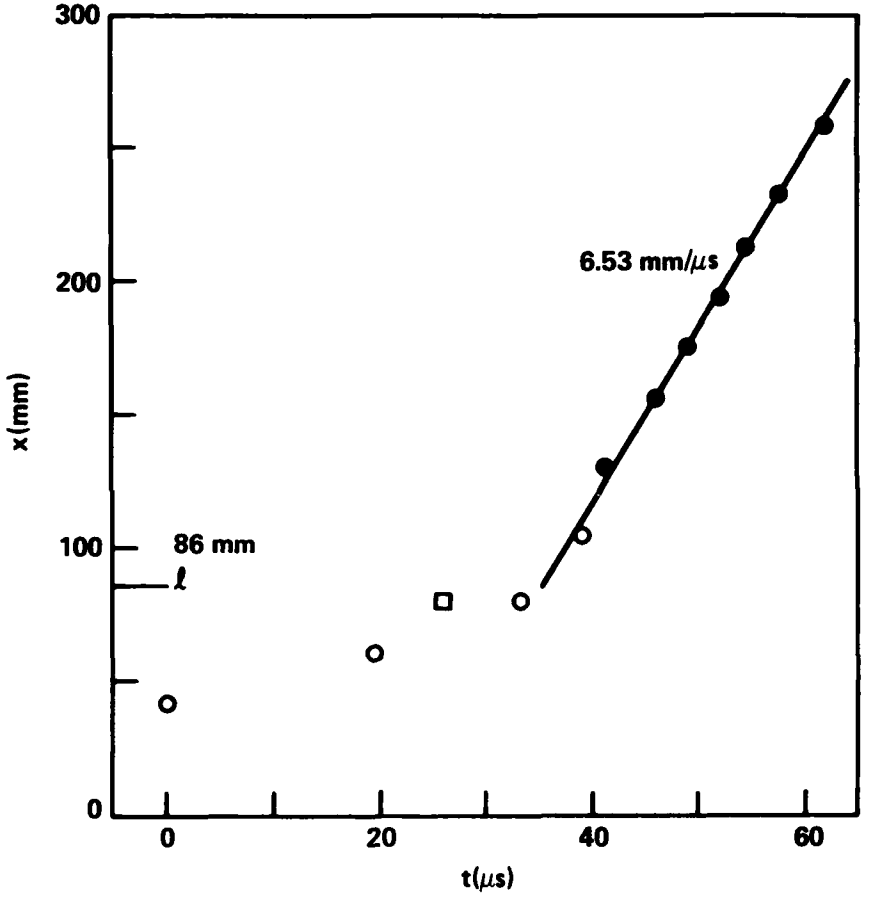
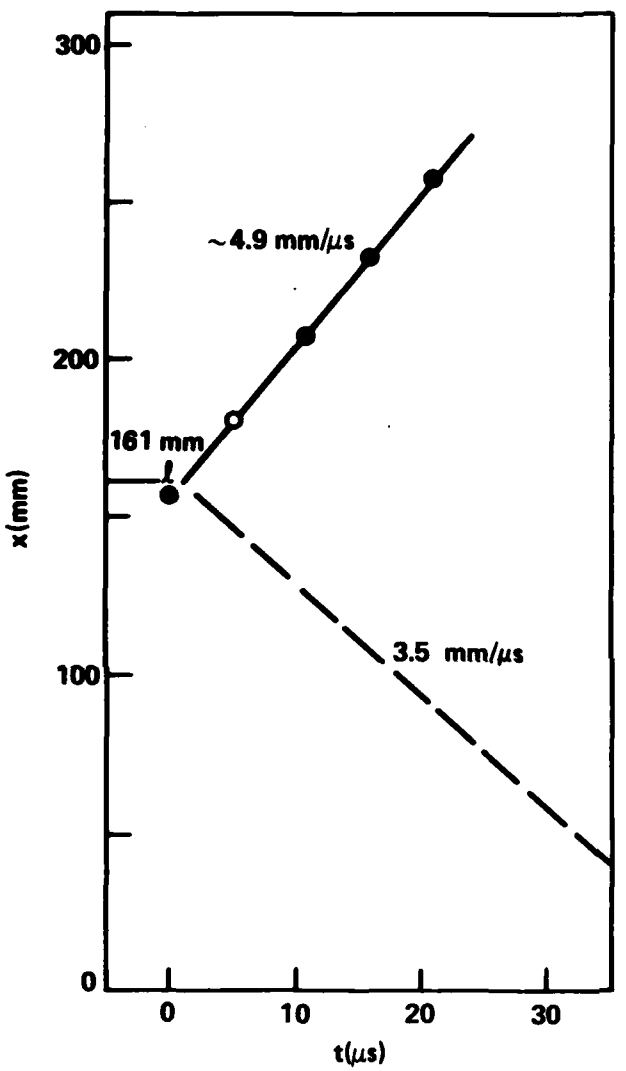
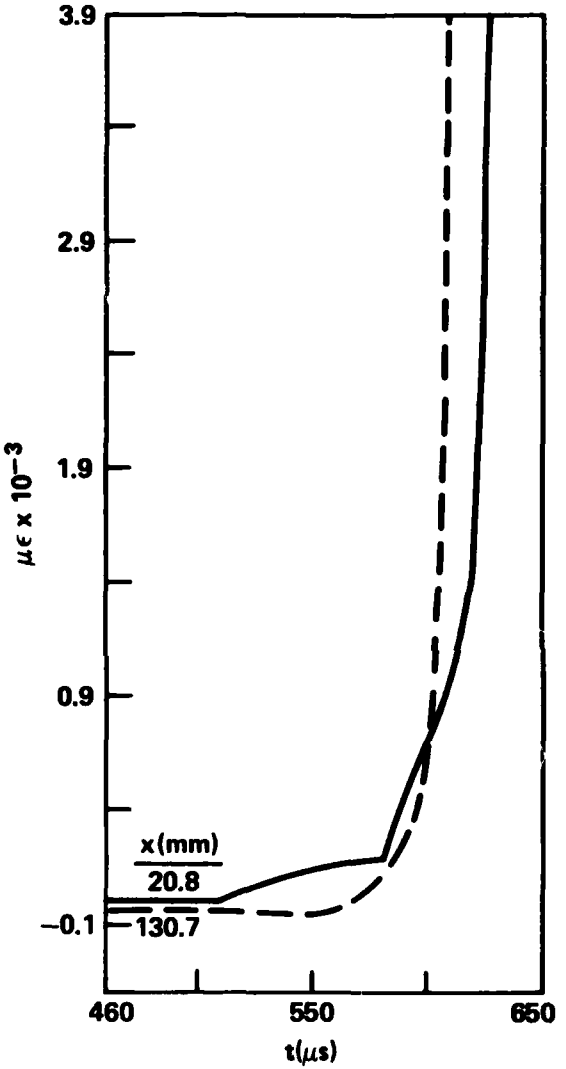


FIGURE A12 DISTANCE-TIME DATA FROM SHOT 1005 ON 91/9 HMX/AP AT 69.5% TMD, ρ_o = 1.32 g/cm^3. (KEY OF FIGURE A1)

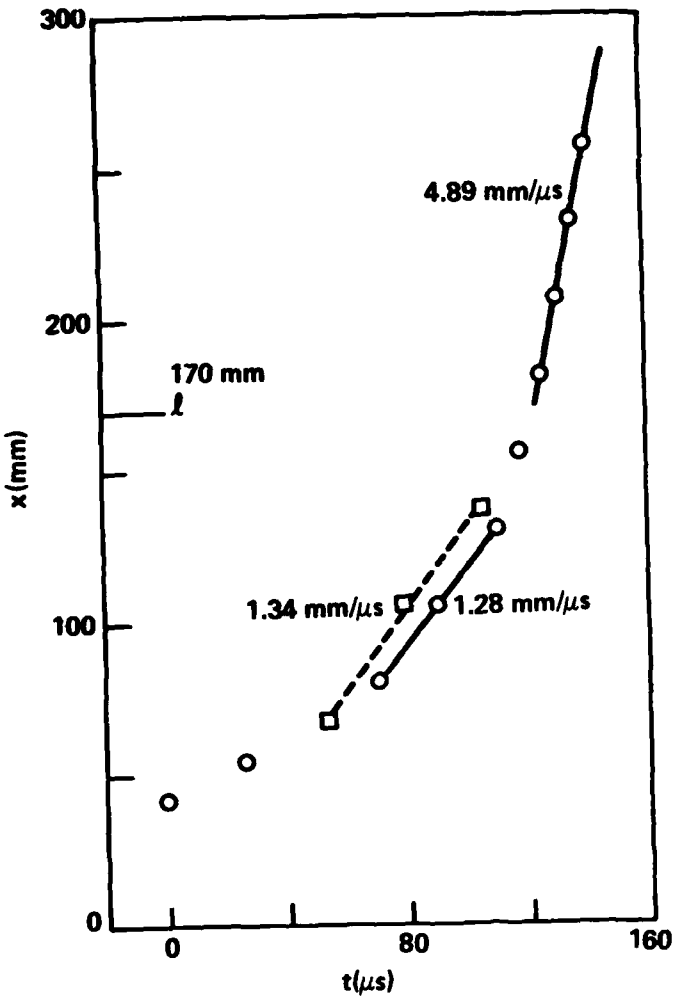


a. DISTANCE-TIME DATA (KEY OF FIGURE A1)

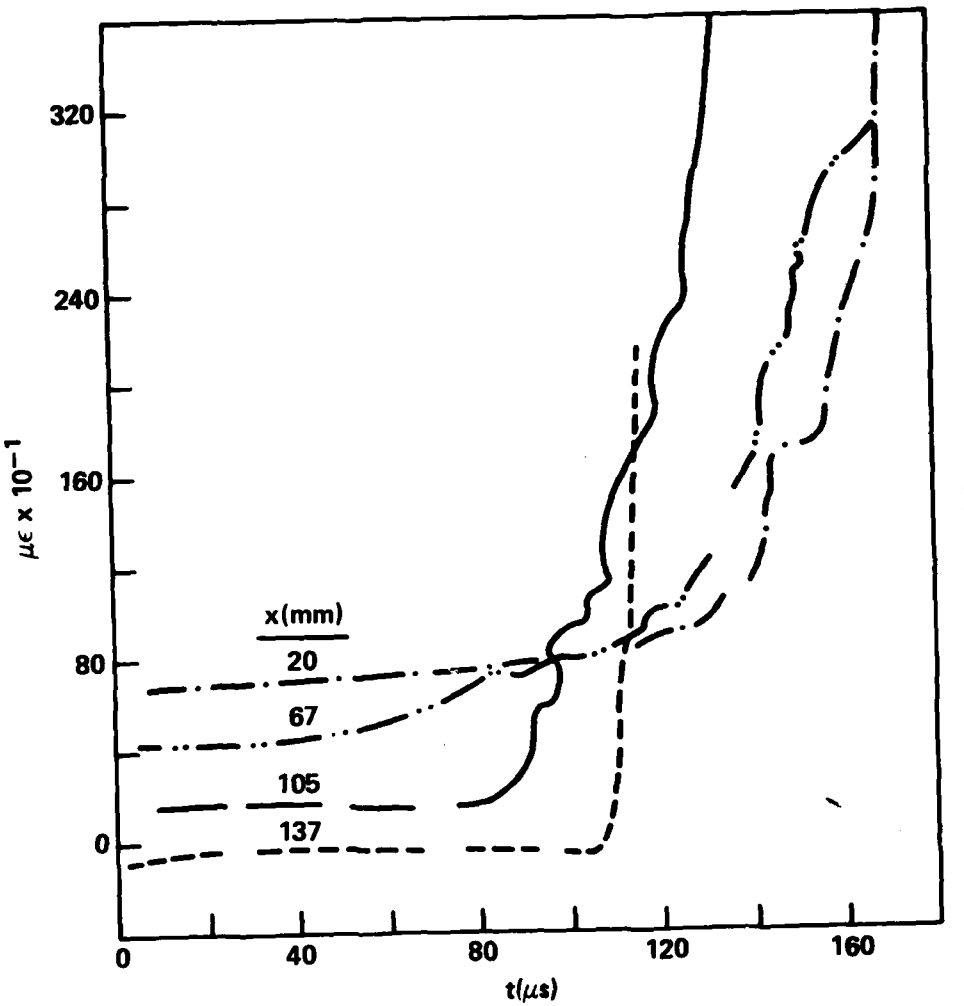


b. STRAIN-TIME DATA

FIGURE A13 DATA FROM SHOT 707 ON 57.3% TMD 25/5/20/50 NC/AP/Aℓ /HMX, ρ_o = 1.11 g/cm^3



a. DISTANCE-TIME DATA (KEY OF FIGURE A1)



b. STRAIN-TIME DATA (KEY OF FIGURE A7b)

FIGURE A14 DATA FROM SHOT 816 ON 67.5% TMD DOUBLE BASE POWDER M-7, ρ_o = 1.10 g/cm^3

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